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AN ANALYTICAL INVESTIGATION OF THE EFFECTS OF ELEVATOR-FABRIC DISTORTION ON THE LONGITUDINAL STABILITY AND CONTROL OF AN AIRPLANE

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SUMMARY

The results of an analytical investigation to determine the qualitative effects of elevator-fabric distortion on the stick-force characteristics of an airplane are presented. These results indicate that serious alteration of intended stick-force characteristics can be produced by elevator-fabric distortion.

INTRODUCTION

Distortion of the surface of fabric-covered elevators has been indicated as a probable cause for large variations in stick force at moderately high speeds. It was of interest, therefore, to make an analytical investigation of the fabric distortions that occur at such speeds and of the effects of these distortions on the stick forces of an airplane in straight dives and constant-speed turns.

METHOD OF ANALYSIS

The analysis was based on an assumed airplane of conventional type with a 30-percent-chord elevator. The selected ratio of elevator chord to rib spacing was 3:1. For this airplane the assumed variations of elevator deflection with airspeed in straight dives and with normal acceleration in constant-speed turns are presented in figures 1 and 2, respectively. Variations of angle of attack of the tail are also shown in these figures.

The distortion of the elevator was determined from the resultant pressures acting on the elevator fabric. External pressures acting over an undistorted elevator were calculated from potential-flow theory by the method of reference 1. Pressure distributions were calculated at speeds of 200, 300, and 400 miles per hour for the straight dives and at normal accelerations of 1, 2.78, 5.56, and 8.33g for the constant-speed turns. The pressure distributions would be somewhat altered by the elevator distortion. Correction was not considered necessary, however, since the pressure changes would merely magnify the distortion without appreciably affecting its mode. Three conditions of internal pressure were used in the analysis: (1) static, (2) positive full dynamic, and (3) negative full dynamic. These conditions represent the ordinary range of internal pressure that can result from venting elevators.

Calculations of the manner in which the fabric deflected under the resulting internal and external pressures acting on the elevator surface were based on hoop-tension theory. (See reference 2.) It was assumed that attachment of the fabric at the elevator hinge line or trailing edge had little effect in restraining deflection at distances greater than one-half the rib spacing from these attachment points. Hoop-tension theory shows that the part of the fabric supported primarily by the ribs will deflect as a section of a circular cylinder when subjected to a uniform pressure. The theory was applied by considering the pressure to be uniform over thin spanwise strips of fabric in a given panel and calculating the average deflection midway between adjacent ribs. The relationship between fabric pressure and fabric deflection as developed from this theory is given by the following formula:

$$p = \frac{64d^3K}{3l^4} + \frac{8dS_1}{l^2}$$

where

p uniform pressure acting on thin spanwise strip

d deflection of spanwise strip midway between ribs

l elevator rib spacing (assumed value, 8 in.)

S_1 fabric initial tension (assumed value, 5 lb per in.)

K fabric modulus of elasticity (assumed value, 500 lb per in.)

A plot of the elastic curve given by this formula for the assumed values of rib spacing, initial tension, and modulus of elasticity is presented in figure 3. These values were chosen because they appear to be typical for standard doped fabric.

The fabric in the vicinity of the elevator nose or trailing edge, being supported on three sides, should deflect approximately as a section of a spherical shell. The deflection curves midway between ribs were accordingly faired with a circular arc from zero deflection at the elevator hinge line or trailing edge to the calculated deflection at one-half the rib spacing from these attachment points.

The effects of fabric distortion on the elevator hinge moments were computed from the change in camber and trailing-edge angle for a chordwise section midway between ribs. The effect of change in camber was determined by approximating the distorted elevator with a multiple-hinged-flap system and computing the hinge moments from data contained in reference 3. The effect of change in trailing-edge angle was determined from data contained in reference 4. All stick forces were corrected to the condition of stick-free trim at 200 miles per hour for the straight dives and to the condition of stick-free trim in level flight for the constant-speed turns.

It has been mentioned that the calculated changes in elevator hinge moments were based on the distortions midway between ribs. This method naturally gives exaggerated effects, as the distortion varies from maximum at this point to zero at the rib itself. It was assumed, furthermore, that the change in normal force on the tail due to fabric distortion could be neglected. This assumption also exaggerates the calculated effects for a given flight condition. These factors do not appreciably alter the trends and relative magnitudes of the calculated changes in stick force. The quantitative values of stick force shown in the figures have been reduced, however, to one-third their calculated values in order that they may correspond more closely to values indicated from flight tests.

RESULTS AND DISCUSSION

Typical modes of fabric distortion for three assumed conditions of internal elevator pressure are presented in figures 4, 5, and 6. The modes of distortion for a given condition of internal pressure are similar in appearance regardless of flight condition. The factors that effect the changes in stick force are the changes in magnitude of the distortion with speed and small changes in mode and relative deflection between upper and lower surface due to flight condition and airplane configuration.

Typical distortions for the static-internal-pressure condition are shown in figure 4. The fabric exhibits a pronounced tendency to bulge along the forward part of the elevator but forms a cusp in the vicinity of the trailing edge. Figure 5 shows typical distortions for the condition of positive full-dynamic internal pressure. As would be expected, both upper and lower surfaces bulge. The distortion reaches such large magnitudes at high speeds that failure of the fabric seems likely. Flight photographs of bulging control surfaces indicate that the sharp curvature in the vicinity of the elevator hinge line and trailing edge is characteristic of fabric distortion under this internal-pressure condition. Typical distortions for the condition of negative full-dynamic internal pressure show that the fabric tends to bow in and the distortion is large enough to draw the fabric completely together in the vicinity of the trailing edge even at the lowest investigated speed. (See fig. 6.) There is therefore no change in trailing-edge angle with speed although this effect might be modified by the presence of a trailing-edge strip.

Figure 7 shows the effect of fabric distortion on the stick-force variation with airspeed for the straight dives and figure 8 shows the effect of fabric distortion on the stick-force variation with normal acceleration for the constant-speed turns. It has been mentioned that these changes in stick forces are chiefly due to the changes in camber and trailing-edge angle of the elevator which result from fabric distortion. The effect of change in thickness at the forward part of the elevator is small and not easily determined. The results of change in camber alone are presented in figure 9 for the straight dives and in figure 10 for the constant-speed turns. The results of change in trailing-edge angle alone are presented in figure 11 for the straight dives and in figure 12 for the constant-speed turns. In general, with static internal pressure the predominant effects on the stick forces are due to change in camber; whereas, with numerically large values of internal pressure the effects are chiefly due to change in trailing-edge angle. The greater effect of change in camber on the stick forces with static internal pressure can be explained by reference to the fabric elastic curve presented in figure 3. The obvious difference in the slope of this curve in the high- and low-pressure ranges shows that numerically high internal pressures serve to stiffen the fabric and, therefore, a given pressure difference between upper and lower surfaces will produce a more extreme dissymmetry of the elevator when the internal pressure is nearly static. The larger effect of change in trailing-edge angle with numerically high internal pressures is due to the greater magnitudes of distortion as compared to those that occur when the internal pressure is nearly static.

The effect of fabric distortion under the investigated conditions of internal pressure on the stick-free longitudinal stability of the assumed airplane for the dive condition are presented in figure 7. The general trend with static internal pressure is toward large increases in stability in the investigated speed range. The chosen stabilizer setting necessitates down elevator to trim the airplane in the upper part of the speed range. This down elevator causes the fabric to bow upwards and thus increases the push force required to hold a given down-elevator deflection. A rough analysis indicates that if the stabilizer were set to require up elevator to trim the airplane, the fabric would bow downward and the direction of the stick-force change would reverse. The magnitudes of the changes in stick force for static internal pressure vary little with center-of-gravity position, but the slope of the curve of stick force against airspeed through the trim speed increases with rearward movement of the center of gravity, because considerably more down elevator is required to trim the airplane at the low speeds with rearward center-of-gravity positions.

The trends corresponding to static internal pressure (fig. 7) appear to have occurred during flight tests of the two airplanes for which the stick-free longitudinal stability characteristics for the dive condition are presented in figure 13. The Bell P-39D-1 airplane required down elevator to trim throughout the upper part of the speed range. A sharp increase is to be noted in the stick forces at high speeds. The dashed curve shows a stick-force variation for the same trim-tab setting based on the assumption that the variations of elevator hinge-moment coefficient with elevator deflection and angle of attack of the tail do not change with speed and, therefore, indicates characteristics to be expected from an undistorted elevator. Conversely, a very sharp decrease in stability at high speed occurred for the Bell P-63A-1 airplane. The tail setting for this airplane, however, necessitated up elevator to trim at high speeds. The trend with up elevator thus corresponds to the effects to be expected from fabric deflection although it is not definitely known whether surface distortion caused the effects in this case.

The general trend with positive full-dynamic internal pressure (fig. 7) is also toward increased stability in the investigated speed range. It appears, however, that a more positive stabilizer setting counteracted by a change in elevator deflection would serve to increase this trend and decreasing the stabilizer setting would produce the opposite effect. The changes in stick forces due to fabric distortion with positive full-dynamic internal pressure are small at forward center-of-gravity positions but large increases in the push forces required to trim are apparent at more rearward center-of-gravity positions. This variation of change in stick forces due to fabric deflection is in a direction to oppose the variation of stick-free stability with center-of-gravity movement. Negative full-dynamic internal pressure results in a trend toward decreased stability at moderately high speeds. This trend also would probably be emphasized by increasing the tail incidence. The variation of the changes in stick force with center-of-gravity position indicates a tendency to exaggerate changes of stick-free stability with center-of-gravity position.

The effect of fabric distortion on the stick forces of the assumed airplane in turns of constant speed is given in figure 8. An increase in the pull force required to obtain a given normal acceleration results from fabric distortion under static internal pressure. These changes in the stick forces are considerably more rapid at fairly low normal accelerations because with the chosen stabilizer setting the elevator goes through its neutral position in the low g range, which causes a reversal in fabric bowing. During turns, the changes in stick force due to fabric distortion under static internal pressure decrease with rearward movement of the center of gravity. This trend exaggerates the effect of center-of-gravity variation on the "force per g" characteristics of the airplane. Fabric distortion under positive full-dynamic internal pressure also results in a trend toward increased pull forces with normal acceleration. The pull forces required increase with rearward movement of the center of gravity. This variation of change in stick force with center-of-gravity movement serves to oppose changes in the force per g characteristics of the airplane with center-of-gravity position. Fabric distortion under negative full-dynamic internal pressure results in small increases in the pull forces required to obtain a given normal acceleration with forward center-of-gravity positions and appreciable decrease in the pull force required with rearward center-of-gravity positions. This trend, like that for static internal pressure, magnifies the effect of center-of-gravity variation on the force per g characteristics of the airplane.

The longitudinal stability characteristics of the Curtiss SB2C-1 airplane, as measured in pull-outs from dives, appear to exhibit some of the effects caused by fabric distortion. The internal pressure of the elevator on this airplane was somewhat negative. Figure 14 shows a plot of force per g normal acceleration against Mach number for a rearward center-of-gravity position. A sharp decrease in the force per g normal acceleration at moderately high speeds is shown, which is an effect to be expected from fabric deflection under a negative internal elevator pressure. Flight photographs of the elevator on this airplane showed that the fabric was being drawn in near the trailing edge.

For cases in which fabric distortion must be tolerated, positive full-dynamic internal pressure would apparently give the most desirable change in stick-force characteristics. Static internal pressure appears to produce the most undesirable changes in stick force with speed, normal acceleration, center-of-gravity position, and tail setting.

SUMMARY OF RESULTS

The general effects of elevator-fabric distortion on static longitudinal stability, which are apparent at moderately high speeds, may be summarized as follows:

Internal pressure nearly static

1. With a stabilizer setting that requires down elevator to trim the airplane at moderately high speeds, stick forces increase rapidly in the push direction with airspeed and the variation of static longitudinal stability with center-of-gravity position increases.

2. With a stabilizer setting that requires up elevator to trim the airplane at moderately high speeds, stick forces increase rapidly in the pull direction with airspeed.

High positive internal elevator pressures

1. Generally, stick forces increase in the push direction with airspeed for usual center-of-gravity positions.

2. The variation of static longitudinal stability with center-of-gravity position decreases.

High negative internal elevator pressures

1. Generally, stick forces increase in the pull direction with airspeed for usual center-of-gravity positions.

2. The variation of static longitudinal stability with center-of-gravity position increases.

The predicted effects of elevator-fabric distortion on elevator-control forces in maneuvers may be summarized as follows:

Internal pressures nearly static

1. Generally, at usual center-of-gravity positions, the force per g normal acceleration F/g increases.

2. Stick forces change rapidly in the range where the elevator passes through neutral.

3. The variation of force per g normal acceleration with center-of-gravity position increases.

High positive internal elevator pressures

1. Generally, at usual center-of-gravity positions, the force per g normal acceleration F/g increases.

2. The variation of force per g normal acceleration with center-of-gravity position decreases.

High negative internal elevator pressures

1. Generally, at usual center-of-gravity positions, the force per g normal acceleration F/g decreases.

2. The variation of force per g normal acceleration with center-of-gravity position increases.

CONCLUDING REMARKS

The analysis indicated that elevator-fabric distortion can produce marked changes on the longitudinal stability and control characteristics of an airplane. If there are cases in which fabric distortion must be tolerated, venting for a high positive internal pressure would seem to give the most desirable change in stick-force characteristics. Such pressures may be dangerous, however, from the standpoint of fabric failure at high speeds. Present conventional venting usually results in internal pressures that are nearly static. This pressure condition appears to produce the most undesirable changes in stick force with speed, normal acceleration, center-of-gravity position, and tail setting.

Careful consideration of stabilizer setting, elevator rib spacing, and elevator venting should therefore precede use of fabric-covered elevators.

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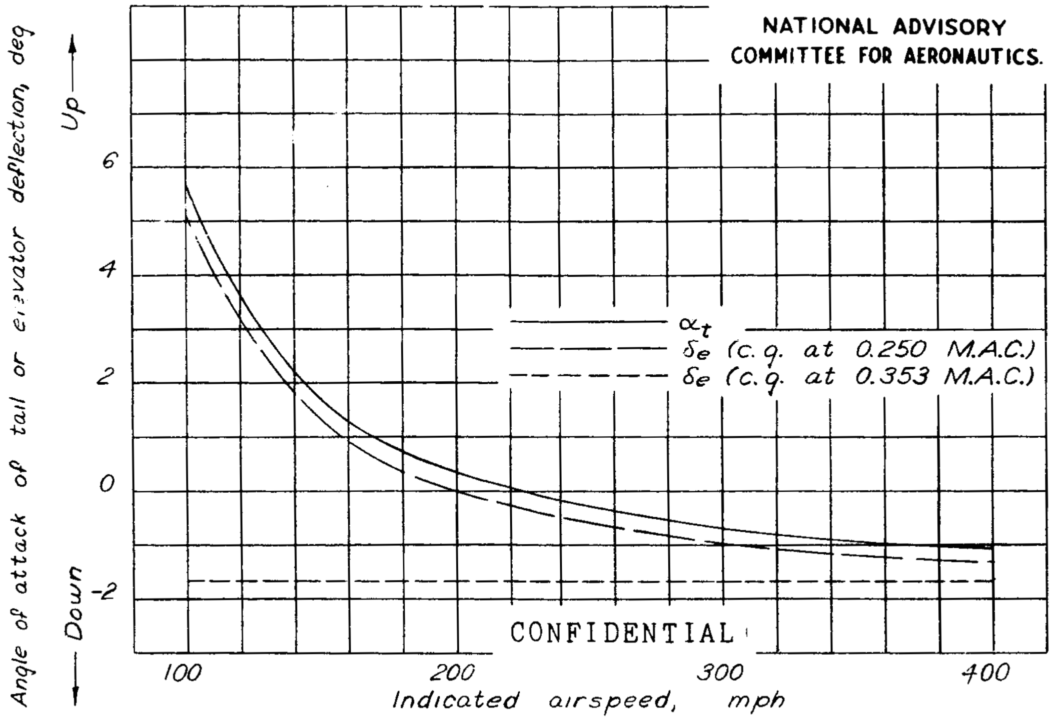

Figure 1.- Variations of elevator deflection δ_e and angle of attack of the tail α_t with airspeed for the assumed airplane. Straight-dive condition.

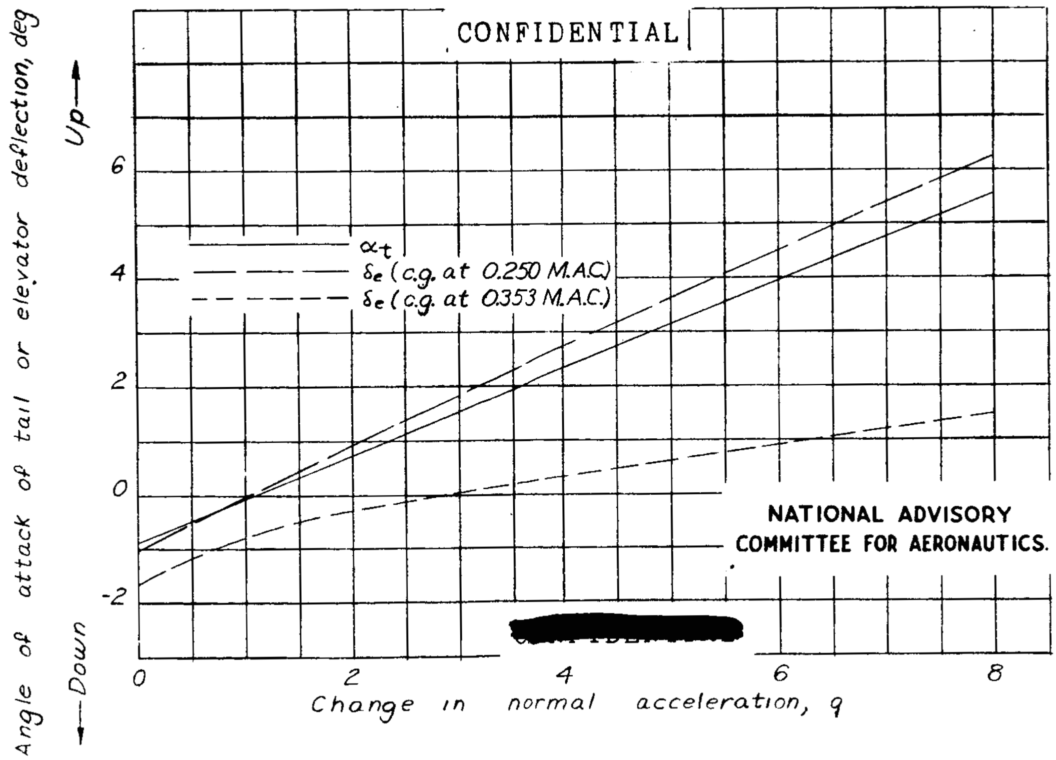

Figure 2.- Variations of elevator deflection δ_e and angle of attack of the tail α_t with normal acceleration for assumed airplane. Turns at 350 miles per hour.

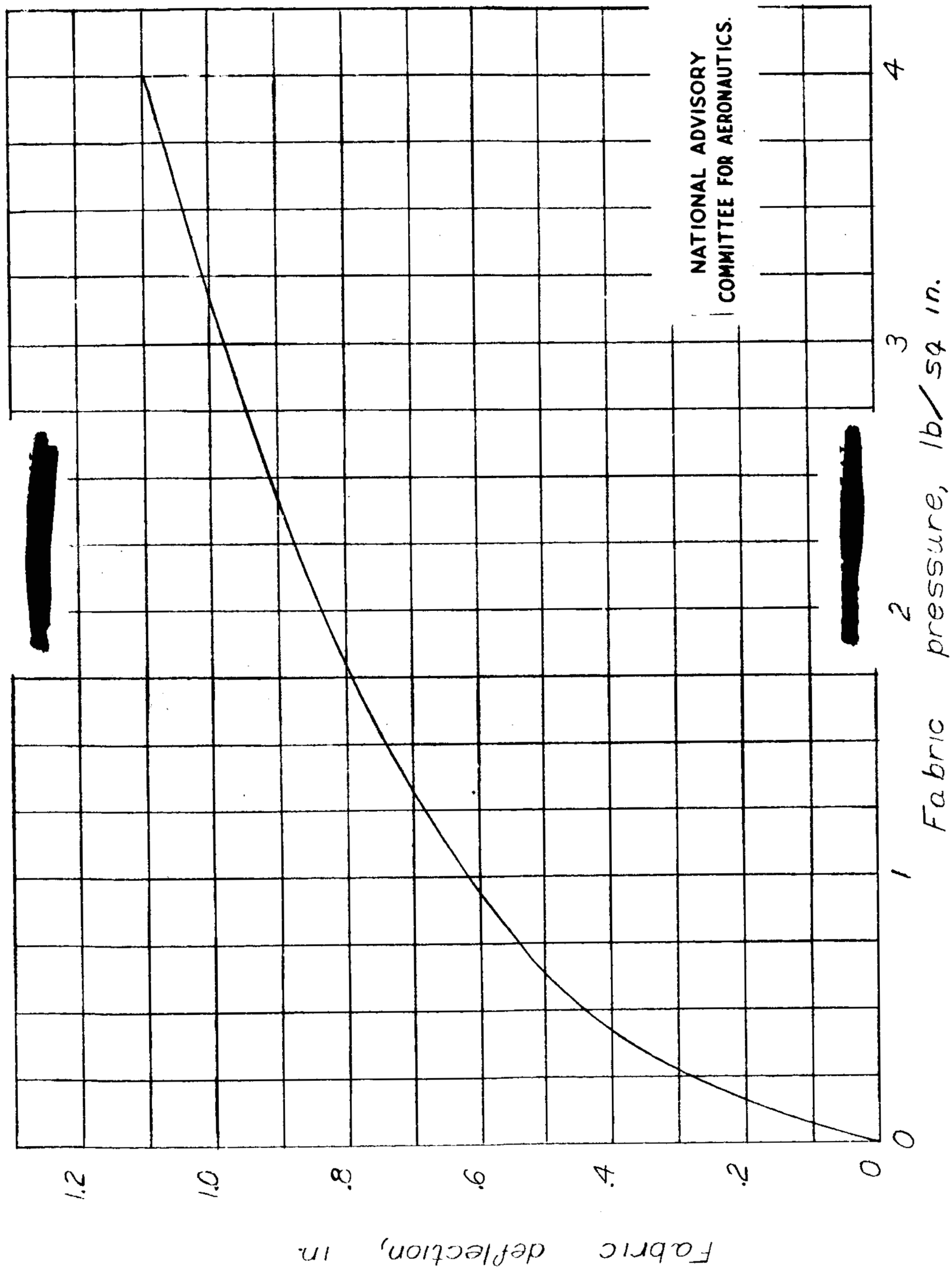

Figure 3.- Elastic curve for fabric panel supported only by two parallel ribs, showing variation of deflection midway between ribs with uniform pressure acting over fabric. Rib spacing, 8 inches; initial tension, 5 pounds per inch; modulus of elasticity, 500 pounds per inch.

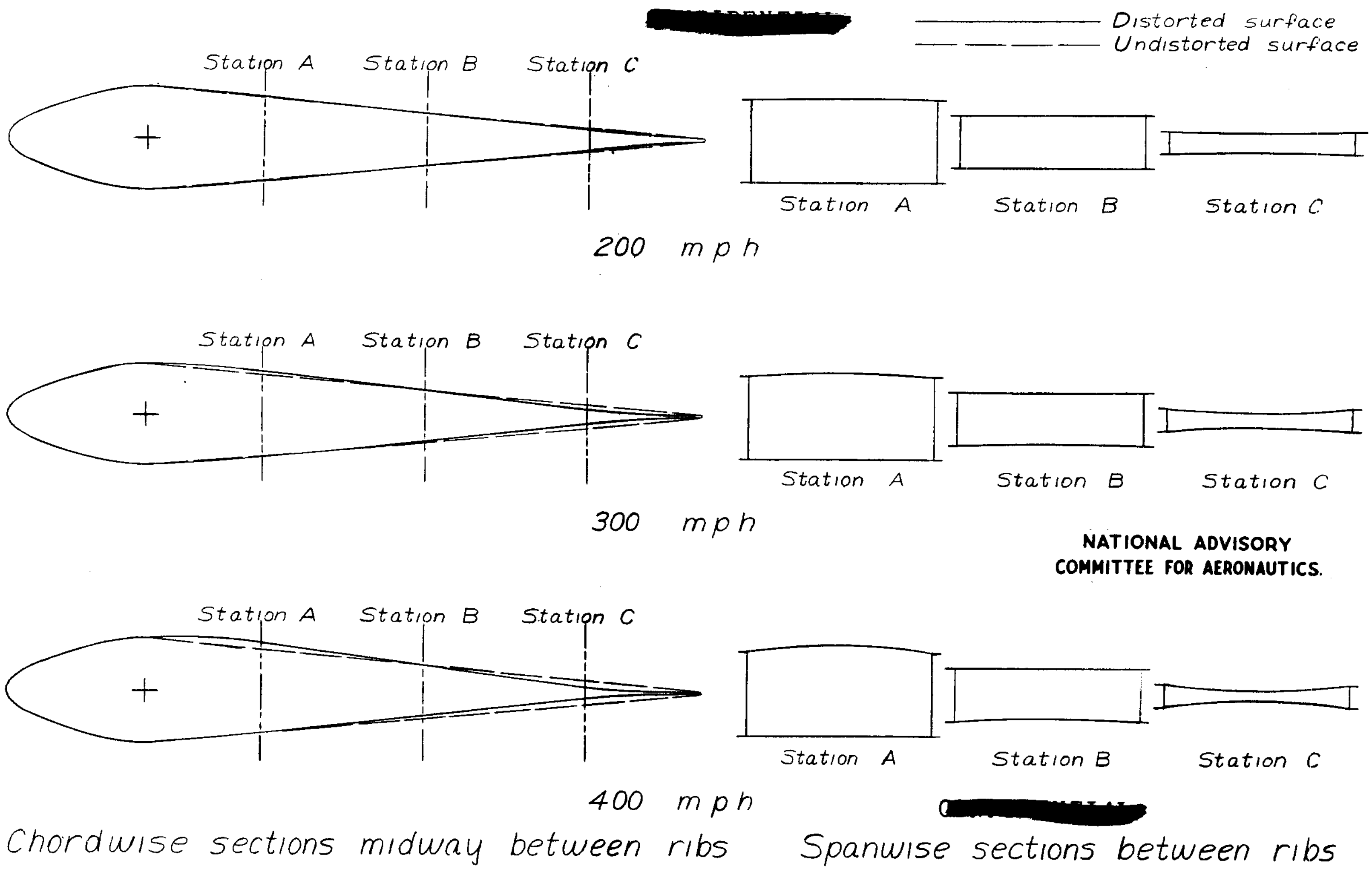

Figure 4.- Typical elevator-fabric distortions under static internal pressure. Elevator is fabric covered from hinge line to trailing edge. Straight-dive condition; c.g. at 0.250 M.A.C.

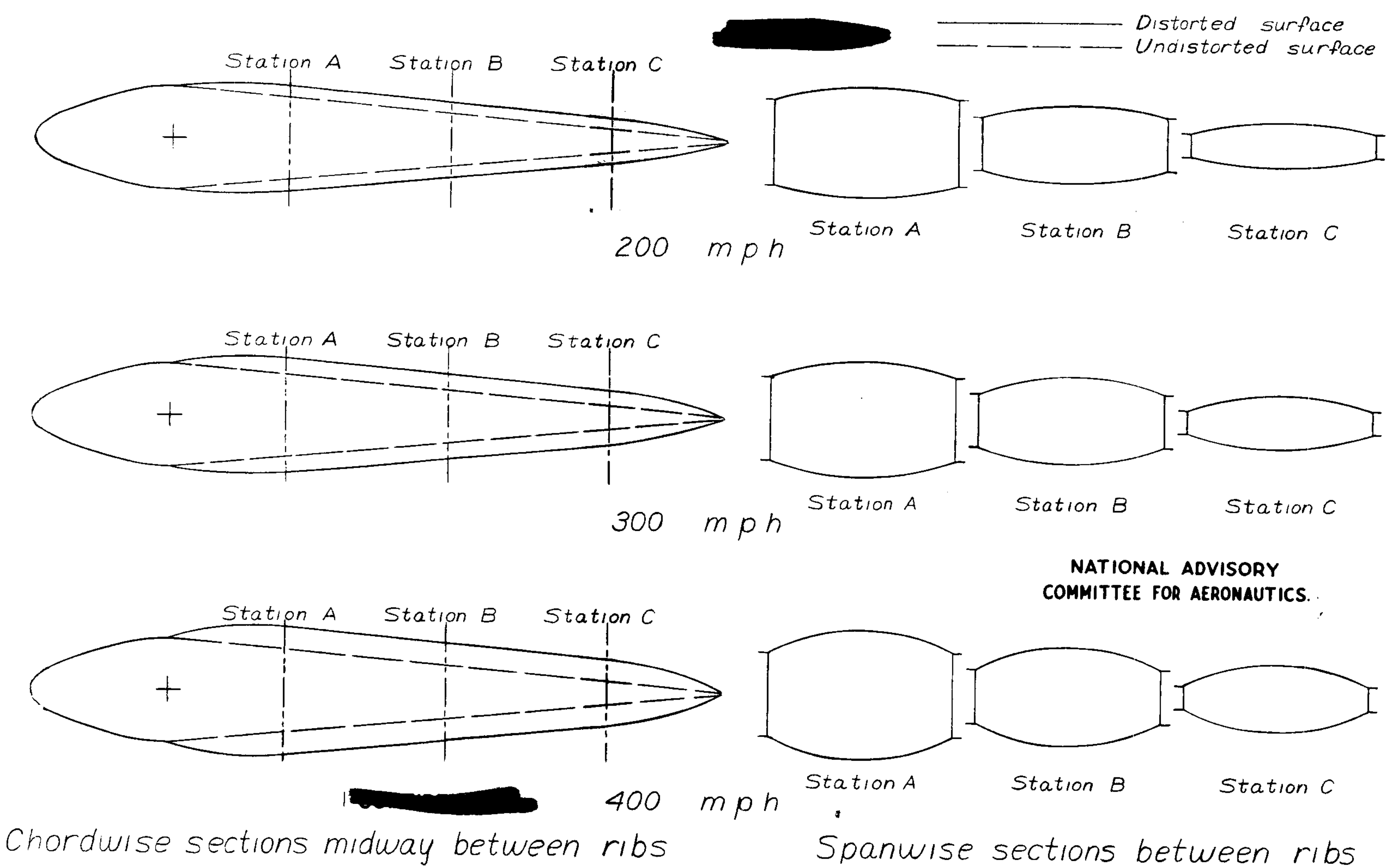

Figure 5.- Typical elevator-fabric distortions under positive full-dynamic internal pressure. Elevator is fabric covered from hinge line to trailing edge. Straight-dive condition; c.g. at 0.250 M.A.C.

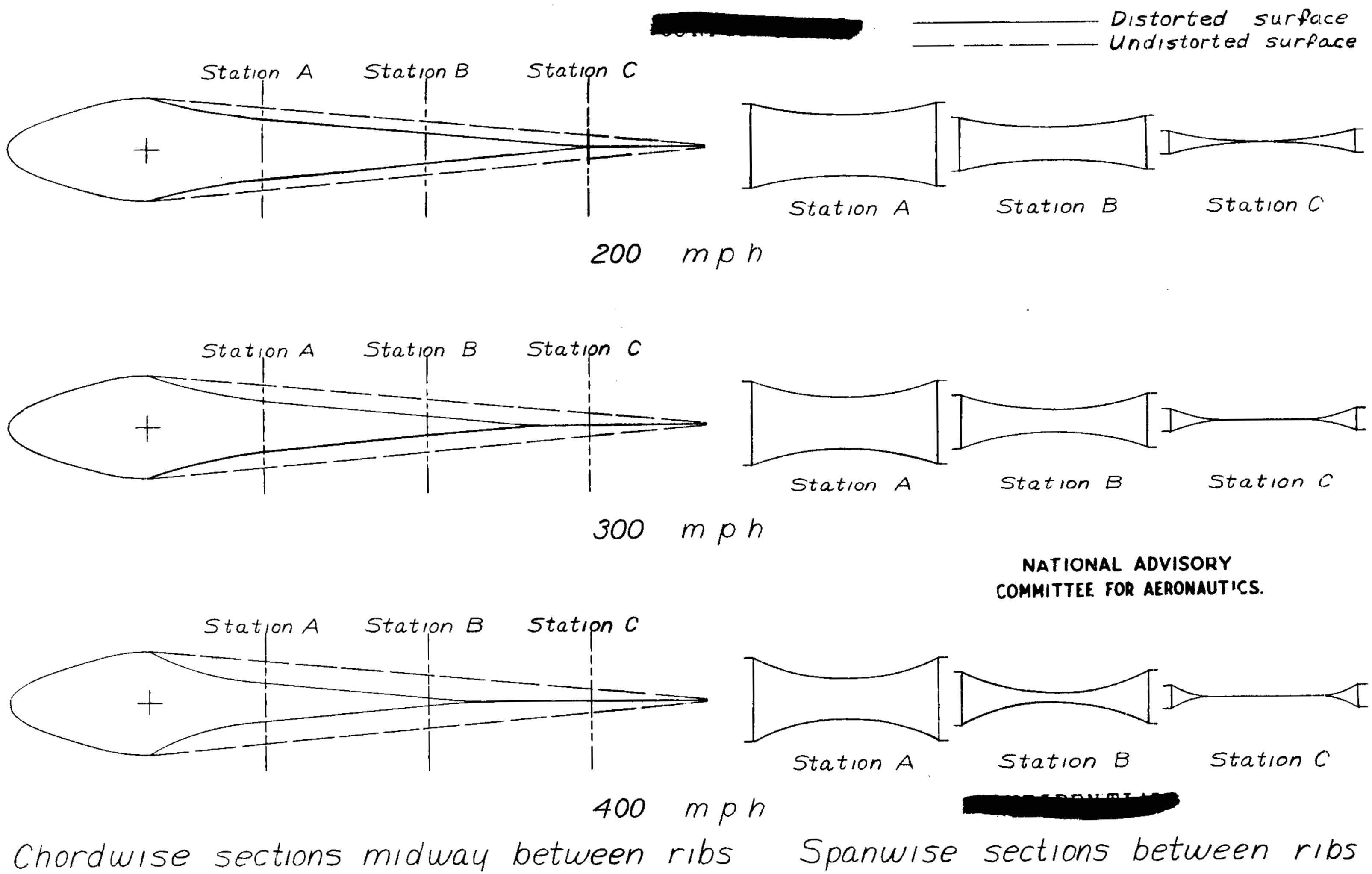

Figure 6.- Typical elevator-fabric distortion under negative full-dynamic internal pressure. Elevator is fabric covered from hinge line to trailing edge. Straight-dive condition; c.g. at 0.250 M.A.C.

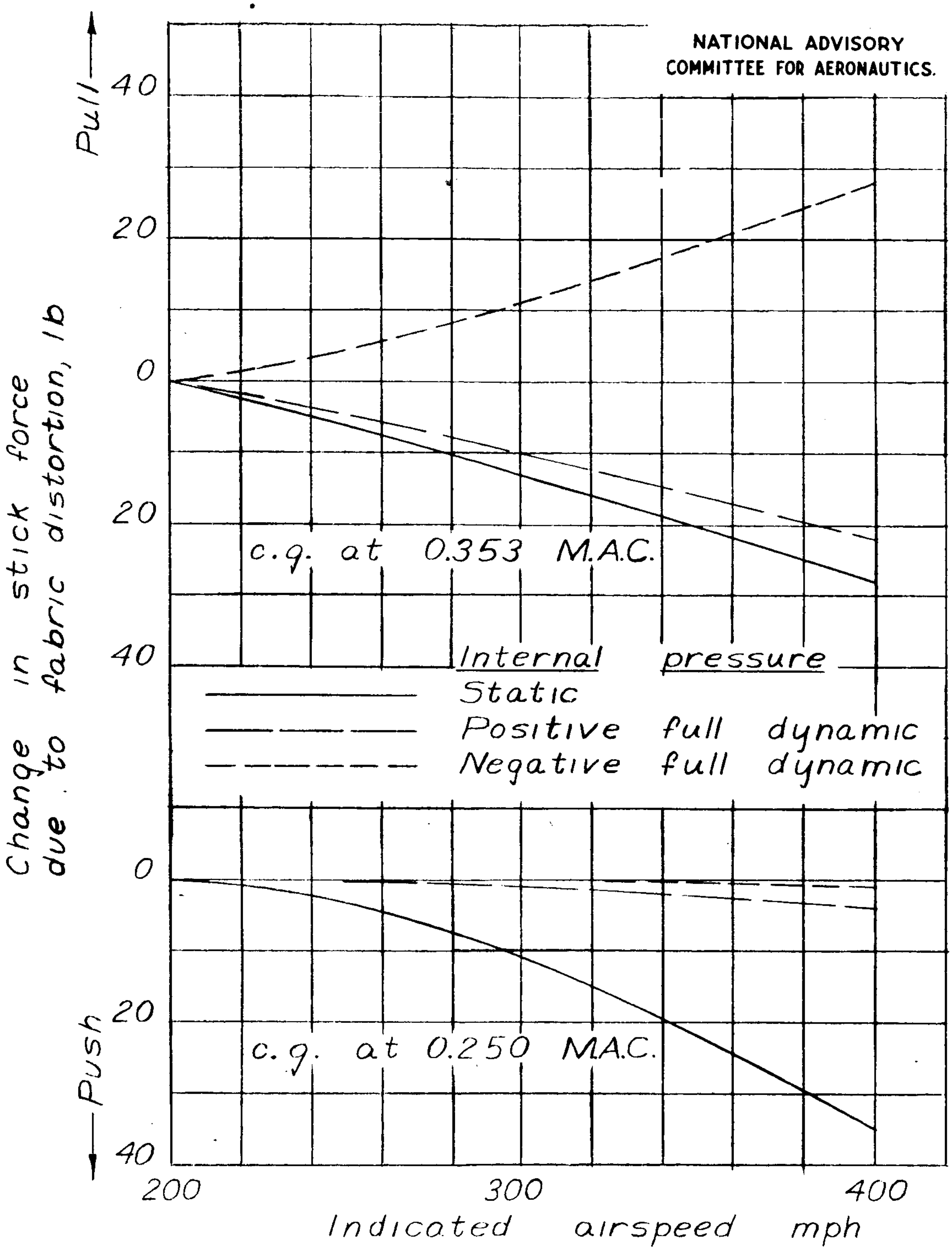

Figure 7.- Difference between stick-force variation with airspeed for undistorted and distorted elevators on assumed airplane, showing combined effect of change in camber and trailing-edge angle due to fabric deflection. Straight-dive condition.

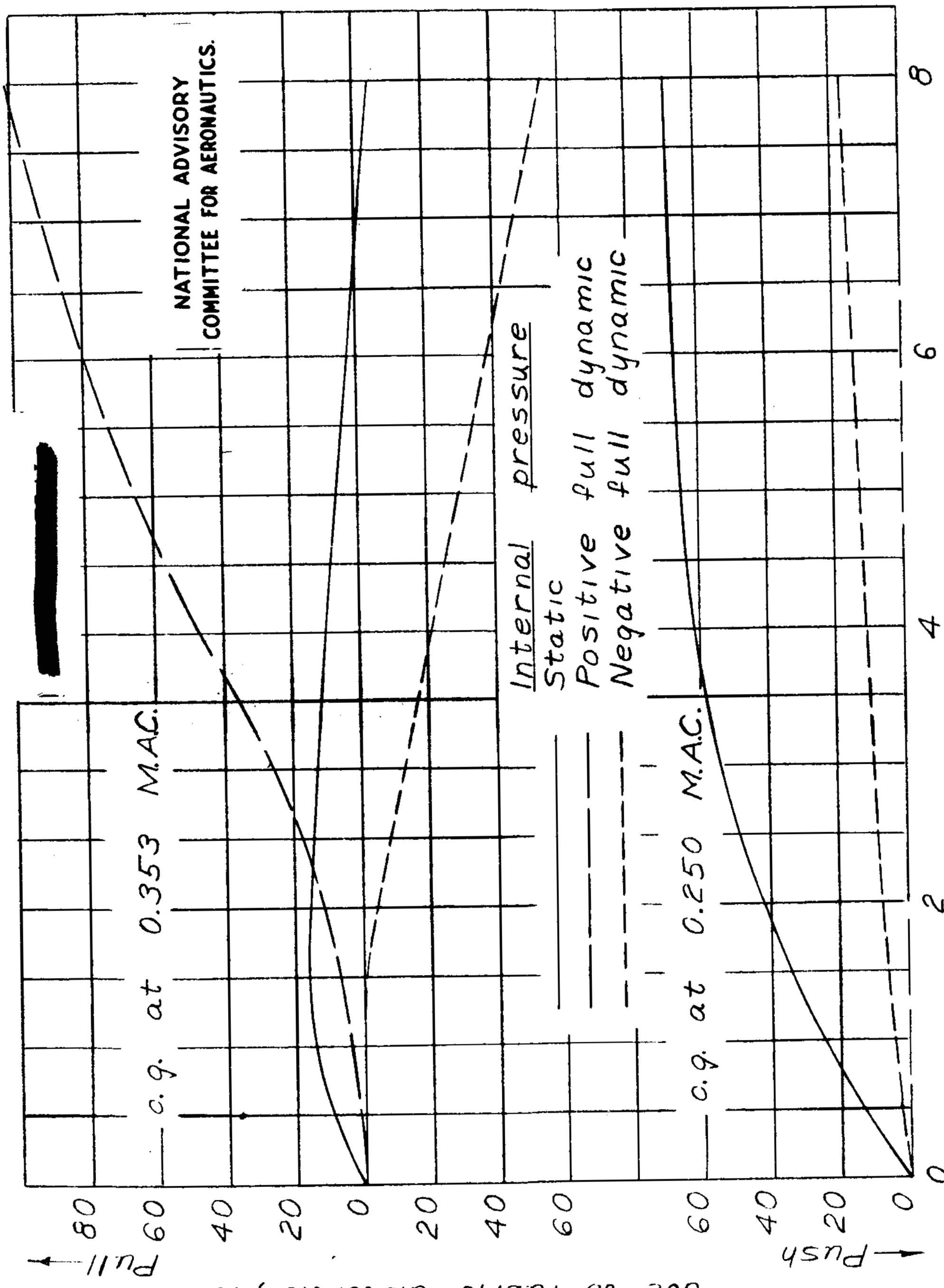

Figure 8.- Difference between stick-force variation with normal acceleration for undistorted and distorted elevators on assumed airplane, showing combined effect of change in camber and trailing-edge angle due to fabric deflection. Turns at 350 miles per hour.

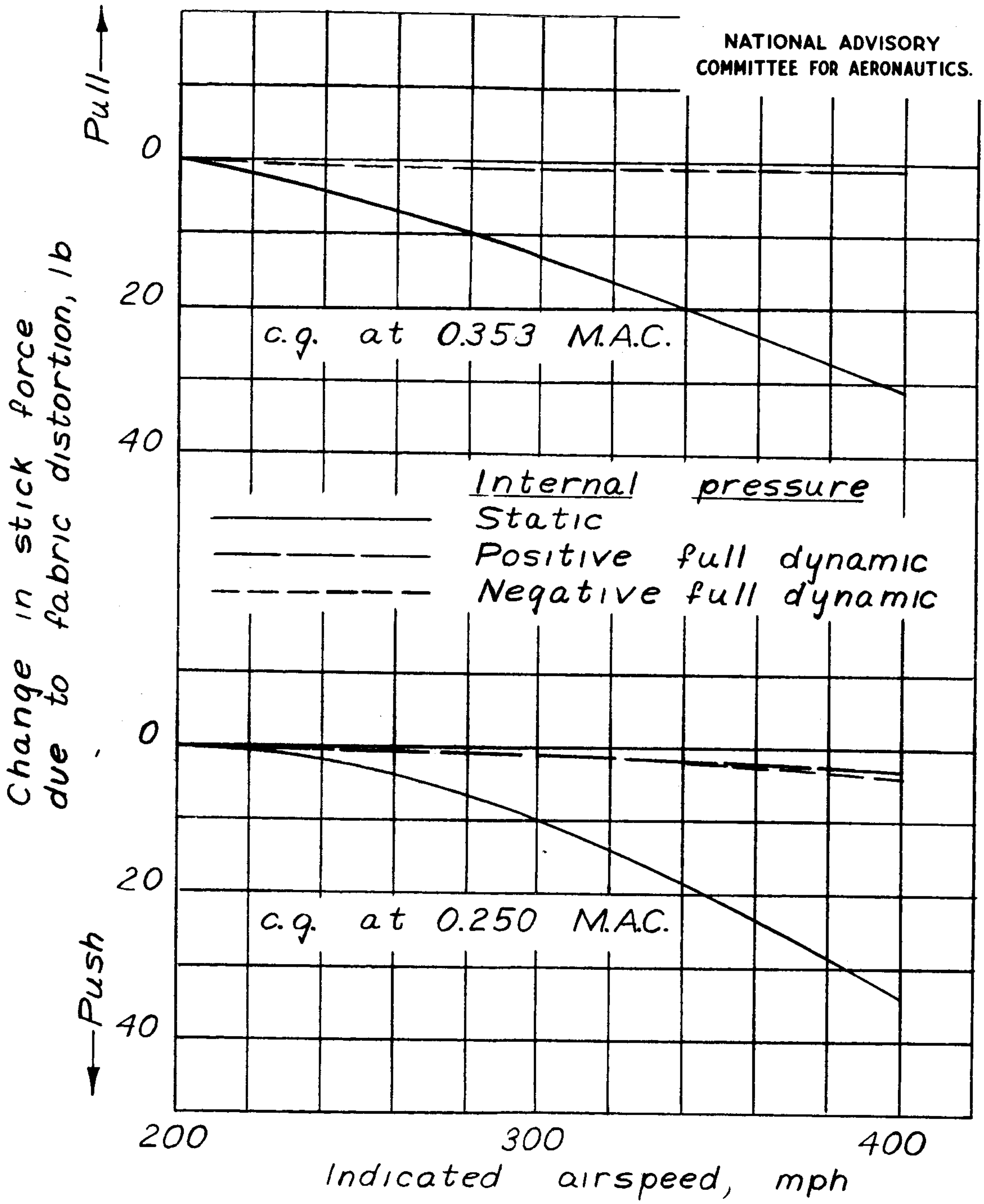

Figure 9.- Difference between stick-force variation with airspeed for undistorted and distorted elevators on assumed airplane, showing effect of change in camber only. Straight-dive condition.

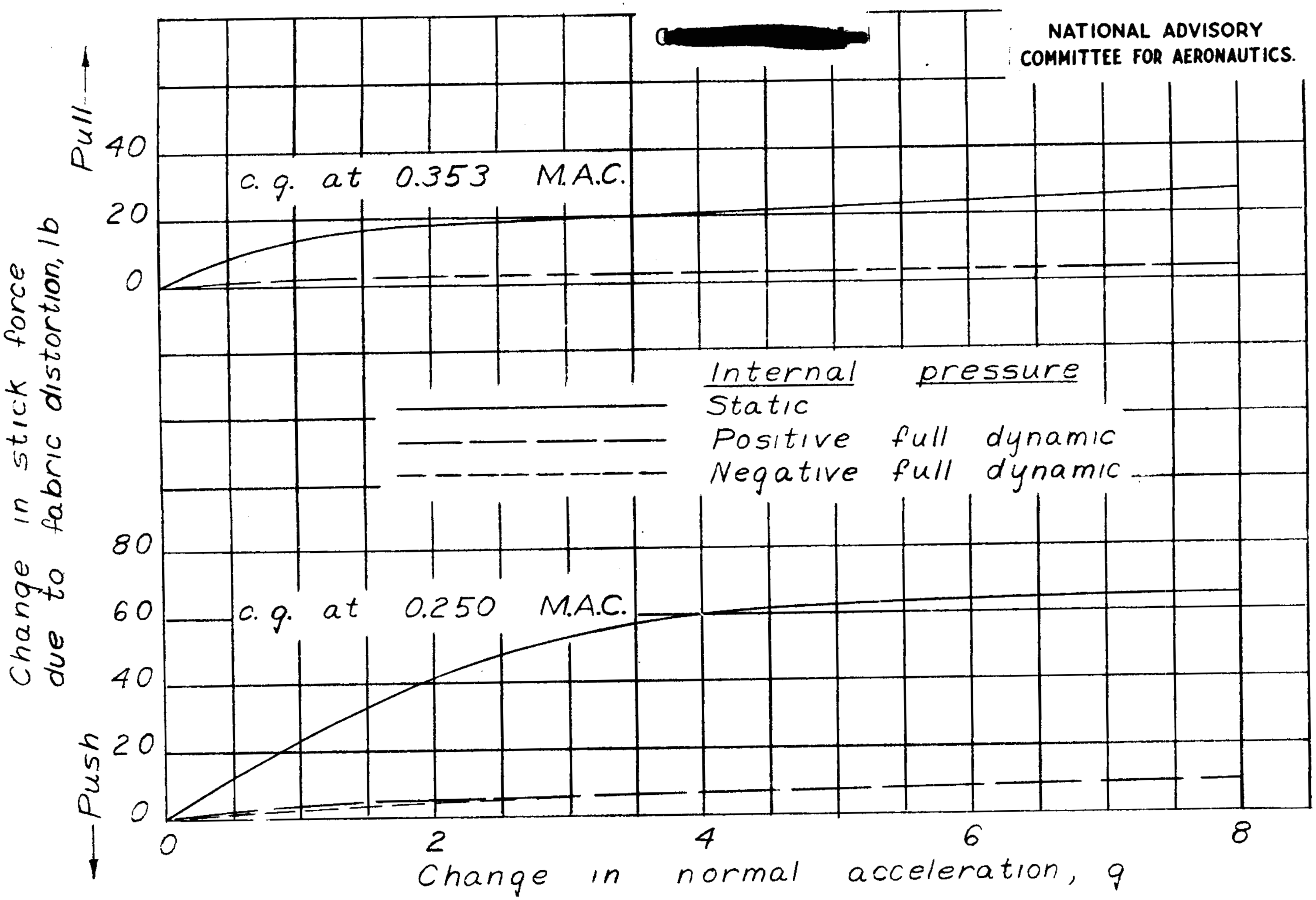

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Figure 10.- Difference between stick-force variation with normal acceleration for undistorted and distorted elevators on assumed airplane, showing effect of change in camber only. Turns at 350 miles per hour.

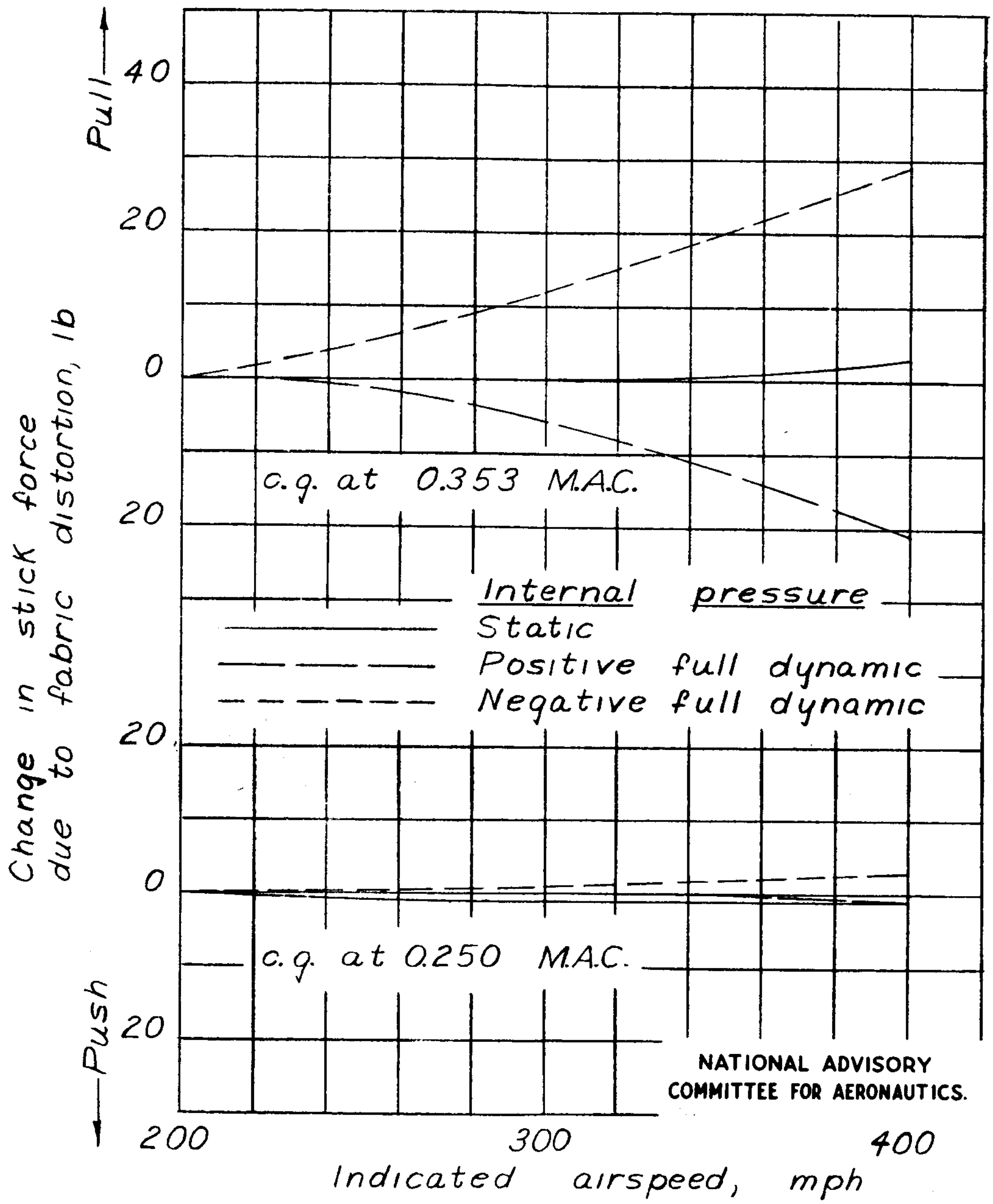

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Figure 11.- Difference between stick-force variation with airspeed for undistorted and distorted elevators on assumed airplane, showing effect of change in trailing-edge angle only. Straight-dive condition.

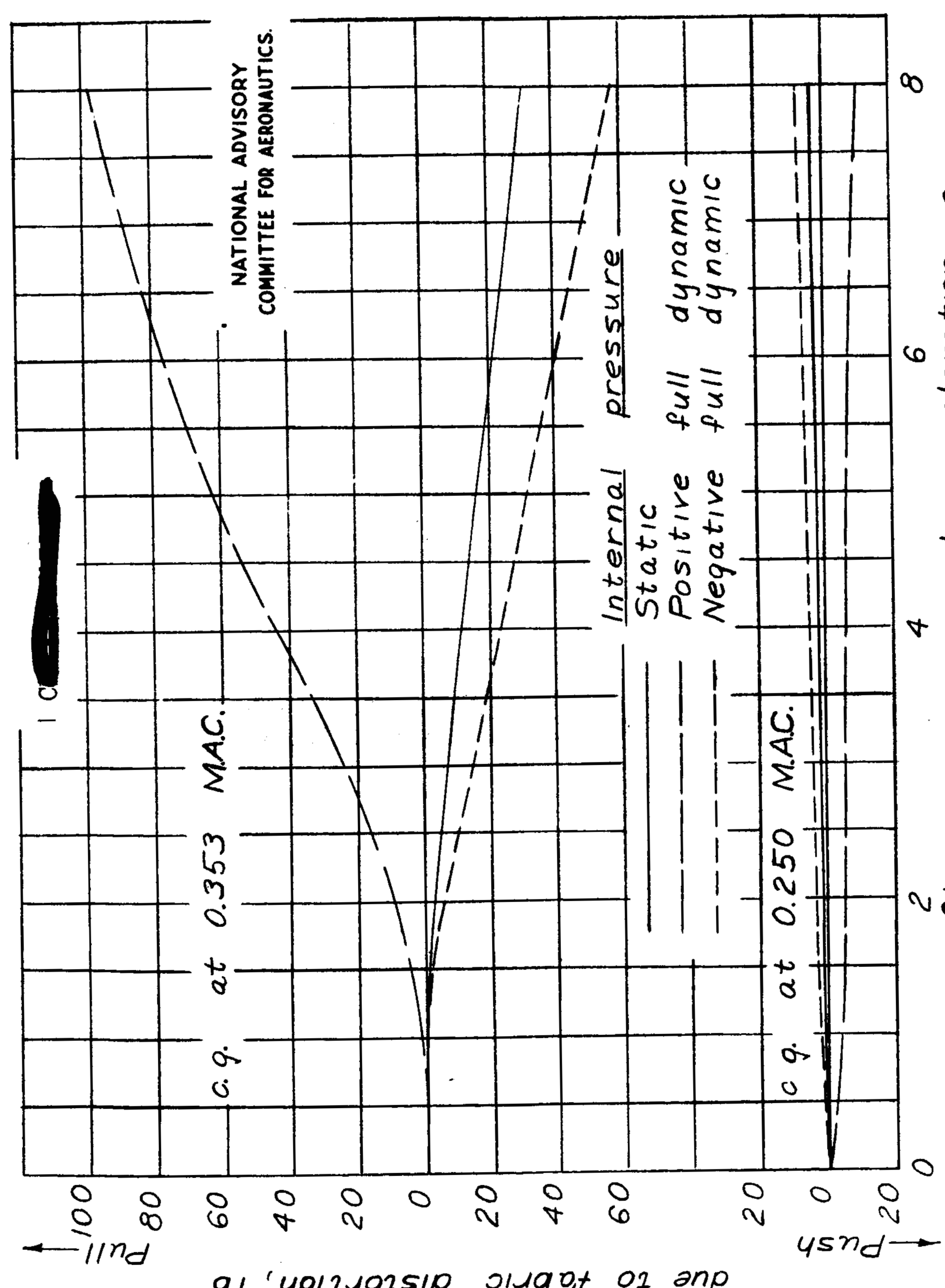

Figure 12.- Difference between stick-force variation with normal acceleration for undistorted and distorted elevators on assumed airplane, showing effect of change in trailing-edge angle only. Turns at 350 miles per hour.

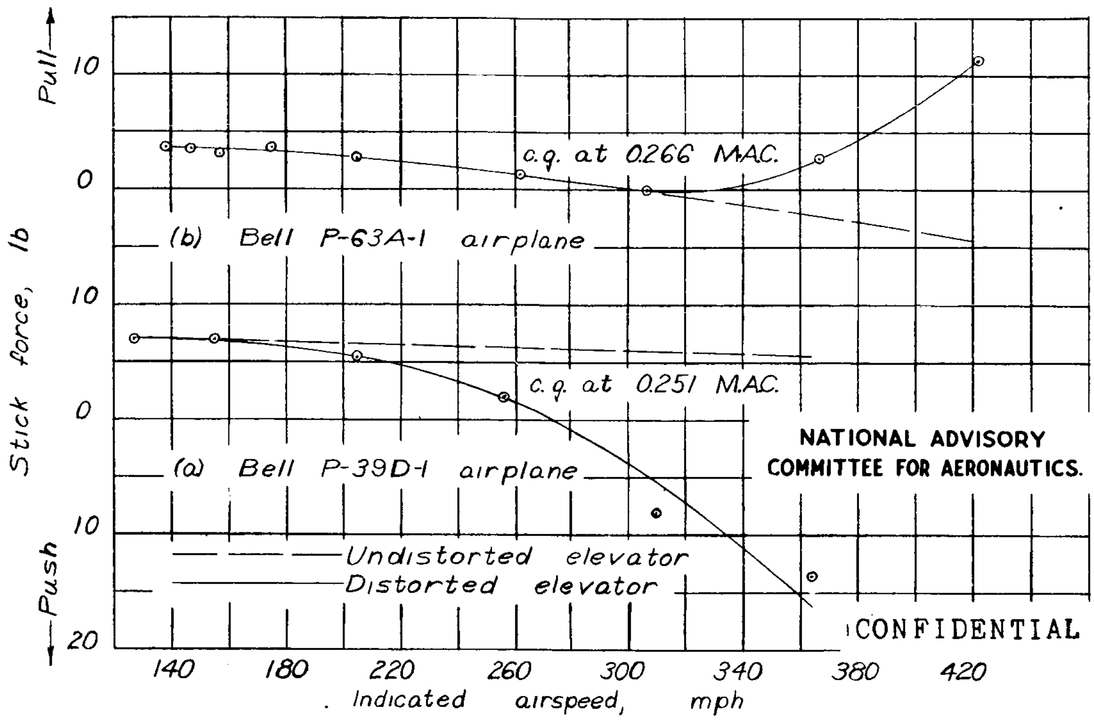

Figure 13.- Static longitudinal stability characteristics (stick free) of the Bell P-39D-1 and Bell P-63A-1 airplanes as measured in flight, showing possible effects of fabric deflection on stick forces at moderately high speeds. Straight-dive condition.

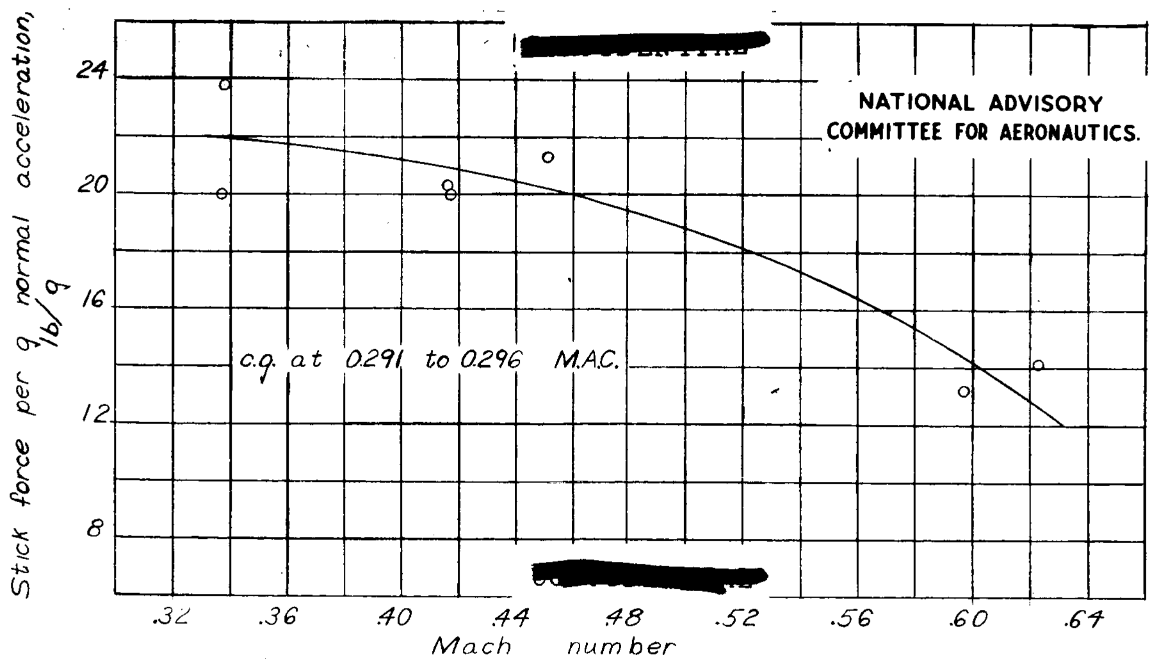

Figure 14.- Variation of force per g normal acceleration with Mach number for the Curtiss SB2C-1 airplane in pull-outs from dives.